Journal of Cleaner Production 174 (2018) 367–379

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Trade-off between productivity and environmental sustainability in irrigated vs. rainfed wheat production in Iran

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A R T I C L E I N F O

Article history:
Received 25 November 2016
Received in revised form
22 September 2017
Accepted 28 October 2017
Available online 30 October 2017

Keywords:
Wheat
Carbon footprint
GHG emissions
Irrigation
Productivity trade-off

A B S T R A C T

Wheat is a strategic crop for Iran with respect to food security and environmental impact. In the northeastern Golestan Province irrigated and rainfed wheat production systems co-exist. In the light of climate change the comparative assessment of the two systems regarding productivity and sustainability is of urgent importance. This paper aims to contribute to a more informed debate on the viability of irrigation in marginal crop production regions. For this purpose, the present study investigates productivity and environmental impact of 540 wheat producing farm households (259 irrigated; 281 rainfed) in Golestan by partial life cycle assessment (LCA) methodology using greenhouse gas (GHG) emissions and product carbon footprint (PCF) as environmental sustainability indicators. The study finds huge heterogeneity among wheat producers with regard to yield, GHG emissions and PCF. Comparing irrigated and rainfed production showed that irrigation in average leads to 22% higher yields. However, the environmental impact of irrigated production is disproportionally high leading to 110% higher GHG emissions and 62% higher PCF, which highlights the trade-off between productivity and environmental sustainability. The major contributors to total GHG emissions of wheat production are energy for irrigation (only in irrigated production), N_2O emissions related to fertilization and residue handling, diesel for machinery, and emissions related to fertilizer production and transport. Increased GHG emissions and PCF in irrigated compared to rainfed production are not only attributed to the energy required for irrigation, but also to increased fertilizer and other production inputs. Splitting the farmers into high, medium and low yield groups indicates the potential for increasing yields through increased input intensity without negative effects on PCF. The study's results demonstrate the potential of better balancing the trade-offs between productivity and sustainability of wheat production in marginal wheat production regions of the world.

1. Introduction

Due to future global population increase, dietary shifts, and growing biofuel consumption, the demand for agricultural crops is going to continuously increase over the coming decades (Godfray et al., 2010). Wheat serves various uses including food, feed and fuel and hence plays a strategic role in realizing future global food security. Wheat is globally the most widely produced cereal (FAO, 2016), constituting the staple crop for about half of the world's population (Nabavi-Pelesaraei et al., 2016).

Wheat experienced an unprecedented productivity increase over the last century, realized mainly by breeding progress and improved input availability (Shiferaw et al., 2013). However, stagnation in wheat yields has been reported for some regions of the world in recent years (Wiesmeier et al., 2015). Globally, wheat yield growth continuously declined over the last decades (Ray et al., 2013), featuring the lowest yield growth rate among the major agricultural crops of the world (Ray et al., 2013). A growing gap between demand and supply is recognized, with wheat production not meeting global demand in ten of the past 15 years (USDA, 2015).

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https://doi.org/10.1016/j.jclepro.2017.10.305
0959-6526/

The projected further increase in global wheat demand is going to aggravate the supply gaps especially in developing countries in the coming decades (Nelson et al., 2010). In the large majority of developing countries the demand for wheat is increasingly met by imports, with wheat already accounting for nearly half of the developing world's food imports (Dixon et al., 2009).

In Iran wheat is of high importance. With around $13 \cdot 10^6$ t of annual production it is the country's number one crop. However, Iran has become one of the world's largest importing countries of wheat in recent years. Since 2000 Iran's wheat imports account to nearly $3 \cdot 10^6$ t $year^{-1}$ in average (FAO, 2016). To overcome the widening supply gaps an increase in wheat production in Iran and other production regions of the world is urgently required. Considering the limited arable land resources and increasing competition with other land uses, it is not viable to increase wheat output by taking more land into production (Godfray et al., 2010), but to increase productivity per land unit (Foley et al., 2011).

Apart from potential technological advances, productivity increases in wheat especially rely on input intensification (Pradhan et al., 2015). This mainly refers to intensified fertilization, plant protection, and mechanization of production, but also to supplemental irrigation (Shiferaw et al., 2013). However, input intensification often entails increased environmental impact, including depletion, degradation and pollution of natural resources (Giuliano et al., 2016). Ensuring environmental sustainability and realizing cleaner production is therefore the key challenge for productivity increase in wheat.

In the present study greenhouse gas (GHG) emissions and product carbon footprint (PCF) were selected as environmental sustainability indicators. Firstly, agricultural production is responsible for about 14% of anthropogenic GHG emissions and hence substantially contributes to global climate change (CC) (Parry et al., 2007). At the same time crop production (including wheat) suffers from the consequences of CC, due to increasing temperatures (Asseng et al., 2011), climatic variability and increase in extreme weather events (Lüttger and Feike, 2017). Hence, assessing wheat production with regard to its climate impact is of great relevance. Secondly, PCF is considered a suitable environmental sustainability indicator of crop production. PCF of grain production is often correlated with other relevant environmental impact indicators, especially eutrophication potential (Griffing et al., 2014) and resource depletion (Nemecek et al., 2011). For other impact categories, e.g., acidification potential (Goglio et al., 2012) or ecotoxicity (Joensuu and Sinkko, 2015) correlations are rather inconclusive. However as also suggested by Pandey et al. (2011) and Weinheimer et al. (2010) PCF is considered a suitable indicator for evaluating the environmental impacts of agricultural activities. Moreover the previous studies demonstrate that PCF used in a LCA approach provides a powerful tool for understanding and developing cleaner food production systems. Hence, it is applied in the present study for the evaluation of wheat production systems.

Previous studies on the environmental sustainability assessment of wheat production using GHG emissions and carbon footprint as indicators are largely based on experimental research. As such, Alhajj Ali et al. (2017) and Gan et al. (2014) tested different tillage and fertilization strategies in Italy and China, respectively. Also wheat crop rotations (Brock et al., 2016) and crop mixtures (Chai et al., 2013) were evaluated for different regions. Other studies built on on-farm experiments (e.g., Cui et al., 2014) or used official statistics to construct prototype wheat production systems (e.g., Casolani et al., 2016; Chiriacò et al., 2017). However, farmers' actual production conditions cannot be captured by such approaches and hence the existing diversity of actual crop management is largely ignored (Feike et al., 2017).

As an alternative approach primary farm data was used in previous studies for the assessment of wheat production systems. By assessing the status quo of production suitable improvement strategies for actual crop management may be developed. However, such previous farm surveys often entail a rather limited sample size. As such, Yan et al. (2015), Ha et al. (2015) and Zhang et al. (2015) obtained production data of 58, 65 and 48 Chinese farmers, respectively. Similar samples were collected from Syp et al. (2015) and Johnson et al. (2016) of 55 Polish and 47 US wheat farms, respectively. To guarantee representativeness for the overall population, larger samples would be strongly desirable to increase robustness and credibility of the obtained results and conclusions. This aim was followed in the present study.

The importance of assessing GHG emissions in Iranian wheat production is underlined by Iran's tremendous increase in GHG emissions, which more than quadrupled since 1980 to about $150 \cdot 10^6$ t $year^{-1}$ nowadays; this makes it the world's ninth largest emitter of GHGs (Boden et al., 2011). Several studies on wheat production have been conducted previously in different regions of Iran. The studies mainly focused on energy use (Ghahderijani et al., 2013; Taghavifar and Mardani, 2015), while fewer also consider GHG emissions per land unit (Soltani et al., 2013; Yousefi et al., 2015). Soltani et al. (2013) report the GHG emissions per unit harvested wheat grain, based on production scenarios run for a single location in northeast (NE) Iran. Moreover, most studies either build on secondary production data (Khoshroo, 2014) or on primary data from small samples (Nabavi-Pelesaraei et al., 2016; Soltani et al., 2013). Furthermore, a crucial shortcoming of all previous Iranian GHG studies is that they only consider nitrous oxide (N_2O) emissions associated to manufacture and transport of inputs, while direct and indirect emissions of N_2O related to crop production are completely neglected (Ghahderijani et al., 2013; Khoshnevisan et al., 2013; Nabavi-Pelesaraei et al., 2016). Direct N_2O emissions stem from cultivated soil, while indirect emissions result from transport of N from crop land into surface and ground waters, or from ammonia emissions. These N_2O emissions are strongly related to fertilization and residue handling (Penman et al., 2000). It is crucial to consider direct and indirect N_2O emissions in GHG accounting as they contribute significantly to overall GHG emissions (Cheng et al., 2015).

With regard to the climate impact of Iranian wheat production irrigation is another important issue. As crop production in Iran is largely conducted under semi-arid conditions (Karimi et al., 2012), irrigation can help to stabilize and increase yields (Shiferaw et al., 2013). Irrigation may hence be a viable means to realize the required productivity increase in wheat. On the other side, there is an increasing competition for scarce water resources in Iran (Karimi et al., 2012), and supplemental irrigation exerts a significant environmental impact. As such, the energy input for irrigation is a major contributor to total carbon dioxide (CO_2) emissions in wheat production (Xu et al., 2015).

Golestan Province was selected as study region, as it features both, rainfed (60%) and irrigated (40%) wheat production (Bureau of Statistics and Information Technology, 2015). Golestan is among the top three wheat producing provinces of Iran and is responsible for about 10% of national wheat production. About $1.1 \cdot 10^6$ t of wheat is produced from 380,000 ha of sown land (Bureau of Statistics and Information Technology, 2015). Golestan is representative for many wheat production regions of Western and Central Asia, which feature climatic conditions that allow rainfed production, while supplemental irrigation is viable but not mandatory (Sayre and Govaerts, 2009). Moreover, Golestan is classified as one of the mega environments for wheat by the International Maize and Wheat Improvement Center (CIMMYT) (Gbegbelegbe et al., 2016).

To the best of our knowledge no study exists that investigates farmers' actual wheat production on such large and thus representative farm survey sample. This allows an unprecedented evaluation of farmers' actual cropping operations, input use, GHG emissions, PCF and yield. Considering the importance of improving the sustainability and productivity of wheat cropping systems and the suitability of Golestan as an example region for coexisting rainfed and irrigated production the study provides new and important insights.

Hence, the present study aims at investigating irrigated vs. rainfed wheat production with regard to its productivity and climate change impact. To be able to develop and adopt improved farming practices and realize cleaner production it is crucial to firstly analyze the status quo of current wheat production in Golestan. The farm as the main management and decision making unit in crop production (Van der Werf and Petit, 2002) was selected for agronomic and environmental assessment. The specific objectives of the study were to (i) quantify GHG emissions and PCF of wheat on farm and county level, (ii) assess the relation of yield with GHG emissions and PCF, (III) understand the contributions of different production factors on GHG emissions, and (iv) identify potential measures to improve farmers' PCF.

2. Materials and methods

2.1. Study region

This study was carried out in Golestan Province, which is located in northern Iran between 36° 30′ to 38° 8′ northern latitude and 53° 51′ to 56° 22′ eastern longitude (Fig. 1). The area of Golestan Province is 20,438 km^2, which accounts for 1.3% of Iran's total area (Bureau of Statistics and Information Technology, 2015). The province is bordered by Turkmenistan in the north, Mazandaran Province and the Caspian Sea in the west, Semnan Province in the south, and north Khorasan Province in the east. Golestan is geographically characterized by the Alburz mountain range in the south and southeast and flat plain regions in the north and northwest. Accordingly, the climatic conditions range from humid temperate to semi-arid temperate climate. In average the study region's mean annual temperature is 18.1 °C, the mean solar radiation is 14.2 MJ m^{-2} d^{-1}, and the total annual precipitation is 565 mm (*cf.* Fig. 2).

Agricultural production in Golestan mainly concentrates in the sub-mountainous regions, which form a strip between the rather wet and cold Alburz mountain range and the rather dry and hot Turkmen Sahra plains in the north, as also illustrated by the distribution of the sampled farms in Fig. 1. Wheat is mostly cultivated as winter wheat, which is sown in autumn during November and December (Soltani et al., 2013). During winter wheat growing season between November and June average temperature is 14.5 °C and sum of precipitation is 420 mm. (*cf.* Fig. 2). Wheat is generally harvested during May and June. In parts of the province wheat is followed by soybean or rice as the second crop in a double cropping system. Other important crops of Golestan are oilseed rape, barley, maize and cotton.

2.2. Data collection

The present study builds on secondary and primary data sources. Secondary information was gathered from peer-reviewed literature, emission databases of the life cycle assessment (LCA) software GaBi 5 (Eyerer, 2012) and Blonk Consultants (Kool et al., 2012), as well as official statistics (Bureau of Statistics and Information Technology, 2015; FAO, 2016). Primary data were collected by farm survey through face-to-face interviews in October 2014 to April 2015. The survey was conducted in cooperation with the local agricultural extension centers of Golestan Province. Within the 14 counties of Golestan a total of 36 extension centers exist. Depending on the crop production area in the different counties the number of extension center ranges from one to five centers per county. Hence, each center is responsible for a similar agricultural production area. During the survey 15 wheat producing farm households were selected randomly in each center as a representative sample of the local production situation. All 540 interviews were conducted by the lead researcher at the farmers' home or a community meeting place.

The farm household heads were selected as interview partners, as they generally are the most influential decision-makers regarding crop management and farm resource allocation. They were interrogated on their average production conditions and respective crop management over the three preceding cropping seasons 2012–2014. The collected information comprises detailed production data including timing, technology and labor requirements of all crop management steps (tillage, sowing, irrigation, etc), timing and amounts of all material inputs (fertilizer, plant protection materials, irrigation water), and specific information on relevant farm and household characteristic (size, age, farming experience, etc). Additional group discussions and key-informant

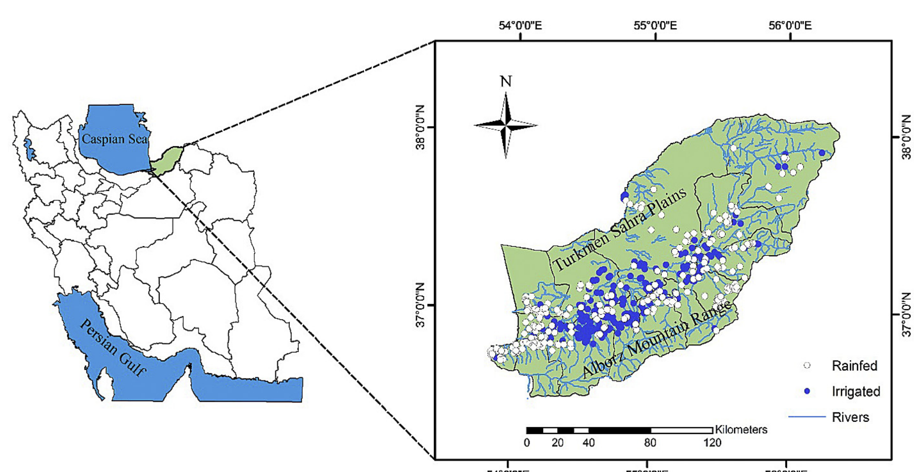

Fig. 1. Location of the study region Golestan Province within Iran (left) and the geographical distribution of the 540 survey sites within Golestan Province (right).

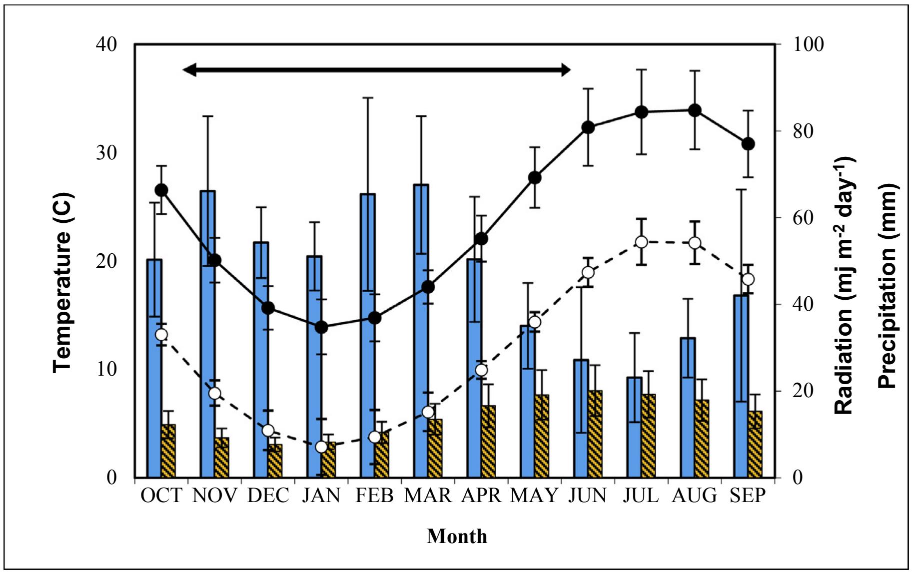

Fig. 2. Long-term (1991–2012) average of monthly minimum temperature (white circles), maximum temperature (black circles), precipitation (blue bars) and solar insolation (yellow-stripe bars) of Golestan Province. The error bars show the deviations over six different weather stations across the province. The horizontal arrow indicates the growing period of wheat.

interviews with the extension experts enabled a holistic understanding of the regional production situation and ensured consistency and plausibility of the collected information.

2.3. Calculation of GHG emissions and product carbon footprint

GHG emission and product carbon footprint were selected as environmental sustainability indicators, representing the environmental impact per unit crop land and unit product for each farm, respectively. The calculations largely follow the International Organization for Standardization (ISO) 14,040 standard (ISO, 2006), and are elaborated in more detail below. Based on ISO 14,040 standard life cycle assessment (LCA) is a tool for evaluating environmental effects of a product, process, or activity throughout its life cycle or lifetime, which is known as a 'from cradle to grave' analysis. According to the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006) global warming potentials (GWP) of the three major GHGs were set as 1, 25 and 298, for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), respectively. GHG emissions per ha and per kg of wheat grain were then expressed in kg CO_2-equivalents (CO_2-eq). Emissions of potential precursors such as carbon monoxide (CO), nitrous oxides (NO_x), and non-methane volatile organic compounds (NMVOCs) are not considered in the present study, as they are not global warming potential-weighted and of limited impact.

A partial life-cycle-analysis (LCA) approach was applied in the present study, which considers all GHG emissions from the initial extraction of input resources to the sale of the final product at the farm gate, i.e., 'from cradle to farm gate' (*cf.* Fig. 3). Emissions stemming from the production of auxiliary materials and agricultural machinery, as well as from human labor were excluded from the analysis. Due to the lack of reliable data on the useful lifetime of auxiliary material and machinery, a thorough accounting of emissions stemming from their production is linked to large uncertainties. Accordingly, the production of machinery is usually excluded from GHG accounting of agricultural production (Villanueva-Rey et al., 2014). Similarly, emissions related to human labor are commonly excluded from GHG accounting (Marras et al., 2015), due to large uncertainties and limited overall contribution.

The calculation of the farm-specific GHG emissions entailed the input stage and field stage emissions. The input-stage emissions consider all GHG emissions released during the production process of the cropping inputs, including fertilizer, plant protection products, seeds and others. Field stage emissions firstly entail the GHG emissions related to energy use for agricultural machinery and irrigation. Secondly, the field stage emissions mainly stem from soil and are largely determined by fertilization and crop residue handling (Dyer et al., 2010). While direct and indirect N_2O emissions are included, CH_4 and CO_2 emitted from soil are considered light sink (Hu et al., 2013) and background emission (Snyder et al., 2009), respectively, and are therefore excluded from the calculation of field stage GHG emissions.

It furthermore needs to be noted, that different ways of residue handling occur among farmers, as illustrated in Fig. 3. Most surveyed farmers sell the wheat straw out-of their farm gate, while stubble and root remains in the field. Some of these farmers, who plant the following crop directly after wheat, burn the remaining stubble to clear their field. This causes additional GHG emissions, which were accounted for following Gupta et al. (2004). Only few farmers remain the straw in their field.

Direct and indirect N_2O emissions from soil were calculated according to IPCC (2006) guidelines as follows:

$$N_2O_{\ total} = N_2O_{direct} + N_2O_{indirect} \tag{1}$$

$$N_2O_{\ direct} = (F_{SN} + F_{ON} + F_{CR}) * EF_1 * \gamma_{N_2O} \tag{2}$$

$$N_2O_{\ indirect} = N_2O_{\ (ATD)} + N_2O_{\ (L)} \tag{3}$$

$$N_2O_{\ (ATD)} = (F_{SN} * EF_4 * Fras_{GASF} + F_{ON} * EF_4 * Fras_{GASM}) * \gamma_{N_2O} \tag{4}$$

$$N_2O_{\ (L)} = (F_{SN} + F_{ON} + F_{CR}) * EF_5 * Fras_{LEACHING} * \gamma_{N_2O} \tag{5}$$

Where F_{SN}, F_{ON}, and F_{CR} represent the N amount of mineral fertilizers, organic materials and crop residues applied to soil (Dubey and Lal, 2009). $N_2O_{\ (ATD)}$, and $N_2O_{\ (L)}$ are N_2O emissions from atmospheric deposition, and leaching and runoff of nitrogen additions from managed soils, respectively. EF_1, EF_4, and EF_5 are the EF_s

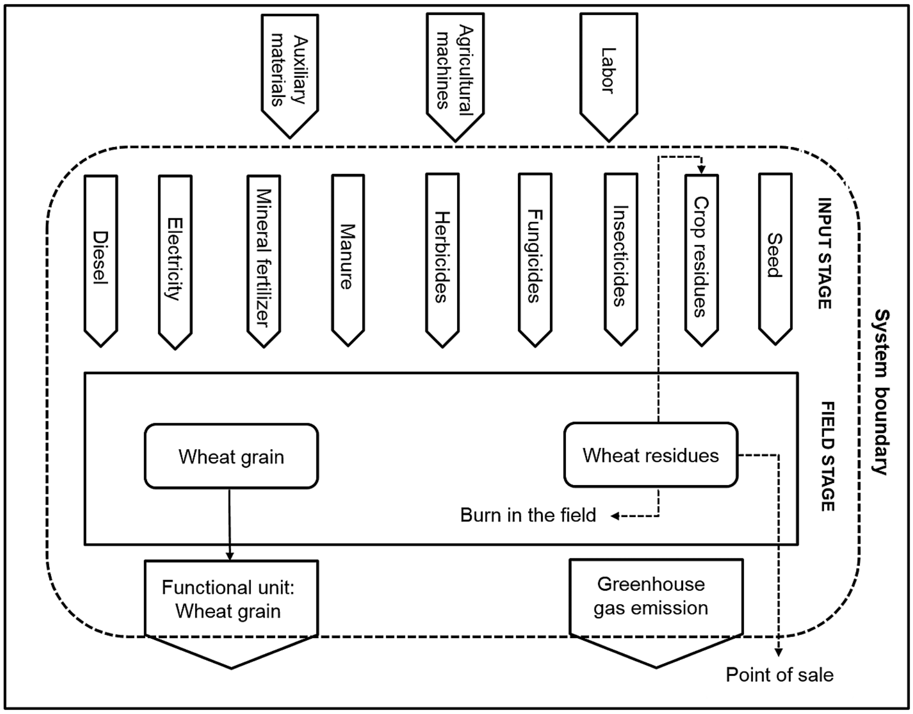

Fig. 3. System description including the system boundary of GHG emission and carbon footprint calculation applied for wheat production in Golestan.

(emission factors) of N_2O emissions from inputs, atmospheric deposition, leaching and runoff of N on soils. $Fras_{GASF}$, $Fras_{GASM}$, and $Fras_{LEACHING}$ are the fraction factors of atmospheric deposition of N volatilized from mineral fertilizer, organic materials, and leaching from managed soil; γ_{N2O} is the mass conversion factor (44/28 g g^{-1} mol mol^{-1}) (IPCC, 2006).

To calculate the farm specific total GHG emissions per ha, the reported cropping inputs and respective crop management technique reported by each surveyed wheat producer in Golestan were linked to the specific EFs presented in Table 2. Finally, the total GHG emissions per unit area expressed in kg CO_2-eq ha^{-1} were converted to PCF of wheat production expressed in kg CO_2-eq kg^{-1} grain as follows:

$$\text{PCF (kg } CO_2\text{-eq kg}^{-1}) = \text{GHG emissions (kg } CO_2\text{-eq ha}^{-1}) \text{ / grain yield (kg ha}^{-1}) \quad (6)$$

An example of step-by-step calculation of a single farm's GHG emissions is presented in the Appendix.

2.4. Wheat production inventory

About half of the surveyed farmers apply irrigation in wheat production, while the other half doesn't. This reflects the general situation in Golestan Province, where additional irrigation may help to bridge critical phases of water shortage, which may occur in years with low rainfall. Then supplementary irrigation can help to ensure high yields. The key-informant interviews of the present study revealed that apart from the farms' specific soil and rainfall conditions, also location, tradition, knowledge and access to water sources influence farmers' decisions of applying additional irrigation. About 90% of farmers use traditional flood irrigation, 10% use sprinkler irrigation and less than one percent use drip irrigation. Nearly 70% of the irrigating farmers rely on ground water, while 32% use surface water. This is in line with Karimi et al. (2012) who report that the use of groundwater has strongly increased in the past few decades in Iran. As most surveyed farmers could not clearly recall the applied amount of energy used for irrigation per unit land, the irrigation energy requirements were estimated based on each farmer's reported irrigation water amount, applied irrigation method and irrigation water source following Jackson et al. (2010) (*cf.* Table 1).

An overview of the applied material and energy inputs of the 540 surveyed wheat producers, including average input amounts and the respective emission factors is presented in Table 2. The input intensity among the surveyed farms shows a strong variability. Even for seed input the intensity differs from 90 to 360 kg ha^{-1}. Accordingly, the energy input for irrigation varies strongly, depending on the applied amount, water source and irrigation method, as described in detailed above (*cf.* Table 1). The applied types of mineral fertilizer are diverse, with Urea and Triple Superphosphate constituting the major sources of N and P, respectively. Only a minor share of farmers uses organic fertilizer as a relevant source of crop nutrients; only 82 and 15 out of 540 farmers applied fresh ruminant and dry poultry manure in their wheat fields, respectively.

A large number of different plant protection products were applied by the surveyed farmers. Product names, active substances, frequencies and amounts of applied chemicals were recorded in detail. However, product specific EFs are not satisfactorily available in literature. Hence, the amounts of the applied products' active ingredients were aggregated separately for herbicides, insecticides and fungicides and employed in the subsequent GHG calculations.

In Golestan's wheat production most crop management steps are mechanized. Farmers' diesel use therefore differs depending on the intensity and frequency of applied measures, e.g. soil tillage, crop protection, fertilization. The largest contributors to diesel consumption are tillage and harvest, while fertilization and sowing require least diesel.

Table 1
Overview of reported irrigation methods and irrigation water sources used to calculate the respective energy requirements for irrigation of the 259 irrigating wheat farmers in Golestan; irrigation energy use is calculated following Jackson et al. (2010).

Irrigation water source	Irrigation method						
	Flood		Sprinkler		Drip		
	Energy use (MJ/ML)[a]	Farmer (%)	Energy use (MJ/ML)	Farmer (%)	Energy use (MJ/ML)	Farmer (%)	Sum of farmers (%)
Surface water	1719	32.0	5845	0	5671	0	32.0
Shallow ground water	3988	24.3	7279	1.2	8014	0.4	25.9
Deep ground water	5982	33.2	10,918	8.5	12,021	0.4	42.1
Sum of farmers (%)		89.5		9.7		0.8	100

[a] Megajoule (i.e., 10^6 J) per Megaliter (i.e., 10^6 L or 10^3 Cubic meter).

2.5. Data handling and statistical analysis

To better understand the existing variability in farmers' performance and investigate the impact of farmers' output level on their environmental impact the farmers were clustered according to their yield levels. Farmers were first split into irrigated and rainfed wheat producers. Then they were clustered into three groups according to their yield levels. Splitting survey samples into subgroups, e.g., tertiles, quartiles or quintiles, for further data analysis based on relevant indicators is widely applied in empirical research (Bezu et al., 2012; Fossati et al., 2017; Weng et al., 2017). Low yielding farmers feature a yield level below the 33rd percentile of all farmers' yields, while medium yielding farmers feature a yield between the 33rd and the 66th percentile of all farmers' yields. The high yielding group of farmers features a yield level above the 66th percentile of all farmers' yields. For irrigated and rainfed wheat production the 33rd percentile yields were 3500 kg ha^{-1} and 2700 kg ha^{-1}, respectively. The 66th percentile yields were 4200 kg ha^{-1}and 3700 kg ha^{-1} under irrigated and rainfed production, respectively.

Data processing was performed using Microsoft Office Excel 2013 and all statistical analyses were conducted using SAS 9.4. Mann-Whitney test was performed to check for differences in yield, GHG emissions, and product carbon footprint (PCF) between irrigated and rainfed production as well as between farmers grouped in yield tertiles. The level of significance was defined at $p < 0.05$.

3. Results and discussion

3.1. Irrigated vs. rainfed production

The average yield of all surveyed farmers is 3482 kg ha^{-1} (Table 3), which is much higher than the Iranian average wheat yield reported for 2011–2013 of about 1950 kg ha^{-1} (FAO, 2016). The higher reported average yield in the present study can mainly be explained by the favorable climatic wheat production conditions of Golestan Province compared to other production regions of Iran. Furthermore a huge heterogeneity can be recognized among all wheat farmers with grain yields ranging from 500 to 6500 kg ha^{-1}, GHG emissions ranging from 373 to 8731 kg CO_2-eq ha^{-1} and PCF ranging from 0.2 to 3.5 kg CO_2-eq kg^{-1}.

Comparing irrigated and rainfed production shows that yield is positively correlated with GHG emissions and PCF, which highlights the trade-off between productivity and environmental sustainability in wheat production. In average yield, GHG emissions and PCF of irrigated wheat production were 22%, 110% and 62% higher

Table 2
Mean values of input flow data, including applied amounts, and respective emission factors of the 540 wheat producers in Golestan; standard deviation, minimum and maximum values are given in parentheses.

Input	Input unit	Input amount	Emission factor (kg CO_2-eq kg^{-1})	Emission factor reference
Seed	kg ha^{-1}	210.4 (36.3; 90–360)	0.19	(Eyerer, 2012)
Energy for irrigation	MJ ha^{-1}	1886 (3120.2; 0–21225)	0.314	(Eyerer, 2012)
Fertilizer				
Diammonium phosphate (N = 18%)	kg ha^{-1}	9.4 (29.0; 0–200)	3.24	(Kool et al., 2012)
Potassium sulfate (K_2O = 48%)	kg ha^{-1}	12.1 (30.9; 0–175)	0.19	(Kool et al., 2012)
Potassium chloride (K_2O = 60%)	kg ha^{-1}	0.7 (7.5; 0–100)	0.56	(Kool et al., 2012)
Triple Superphosphate (P_2O_5 = 48%)	kg ha^{-1}	78.1 (56.5; 0–310)	0.36	(Kool et al., 2012)
Urea (N = 46%)	kg ha^{-1}	191 (82.0; 0–500)	3.63	(Kool et al., 2012)
Ammonium sulfate (N = 21%)	kg ha^{-1}	0.3 (4.5; 0–92)	2.28	(Kool et al., 2012)
Organic sulfur (S = 10%)	kg ha^{-1}	7.3 (37.3; 0–350)	0.63	(Eyerer, 2012)
Sulfur bentonite (S = 60%)	kg ha^{-1}	2.5 (15.1; 0–130)	0.0252	(Umweltbundesamt, 2016)
NPK compound (N:P_2O_5:K_2O = 15:8:15)	kg ha^{-1}	1.8 (15.0; 0–250)	4.59	(Kool et al., 2012)
Fresh ruminant manure	kg ha^{-1}	1717.6 (5804.9; 0–50000)	0.044	(Eyerer, 2012)
Dry poultry manure	kg ha^{-1}	12.8 (175.6; 0–4000)	0.24[b]	(Ecochem, 2016; Lal, 2004)
Agricultural chemicals				
Herbicides	kg a.i.[a] ha^{-1}	0.2 (0.3; 0–5.52)	23.1	(Lal, 2004)
Fungicides	kg a.i. ha^{-1}	0.2 (0.1; 0–0.95)	14.3	(Lal, 2004)
Insecticides	kg a.i. ha^{-1}	0.01 (0.1; 0–1.14)	18.7	(Lal, 2004)
Diesel for machinery				
Soil tillage	liter ha^{-1}	56.7 (21.3; 9.1–239.9)	3.5	(Eyerer, 2012)
Sowing	liter ha^{-1}	7.9 (3.9; 0–18)	3.5	(Eyerer, 2012)
Fertilization	liter ha^{-1}	3.5 (3.3; 0–17.9)	3.5	(Eyerer, 2012)
Crop protection	liter ha^{-1}	10.2 (5.8; 0–35)	3.5	(Eyerer, 2012)
Harvest	liter ha^{-1}	31.4 (5.1; 15.1–44)	3.5	(Eyerer, 2012)
Transportation	liter ha^{-1}	17.2 (3.1; 7.9–33.8)	3.5	(Eyerer, 2012)

[a] .i. = active ingredient.
[b] Details of calculation are presented in the Appendix (Table 6).

Table 3
Average values of yield, GHG emissions, and product carbon footprint (PCF) of the surveyed wheat farms in Golestan, grouped according to irrigated and rainfed production; standard deviation, minimum and maximum values are given in parentheses. Different letters behind the average values (a-b) indicate significant differences at 5% level as determined by Mann-Whitney test.

	Yield (kg ha^{-1})	GHG (kg CO_2-eq ha^{-1})	PCF (kg CO_2-eq kg^{-1})	Number of farmers (N)
All farmers	3482.1 (1050.1; 500–6500)	2447.8 (1416.4; 373.5–8730.6)	0.71 (0.4; 0.2–3.5)	540
Irrigated	3848.5a (901.3; 1200–6500)	3367.8a (1467.6; 1024.2–8730.6)	0.89a (0.4; 0.3–2.7)	259 (48%)
Rainfed	3144.5b (1064.2; 500–6250)	1600.2b (609.6; 373.5–5164.9)	0.55b (0.3; 0.2–3.5)	281 (52%)

compared to rainfed production, respectively. Firstly, irrigation leads to significantly higher yields, which are in average about 700 kg ha^{-1} higher than rainfed yields. However, this observed difference between irrigated and rainfed production is much smaller compared to the difference reported by Soltani et al. (2013) of more than 1700 kg ha^{-1}. They determined 4240 kg ha^{-1} and 2500 kg ha^{-1} for irrigated and rainfed wheat production in the western part of Golestan, respectively. Even higher yield differences were determined by Yousefi et al. (2015) in Kermanshah Province in western Iran, with grain yields differing between 7000 kg ha^{-1} and less than 2000 kg ha^{-1} in irrigated and rainfed production, respectively. The different results between the present and previous studies can largely be explained by differences in natural production conditions, especially differences in the crop water supply-demand-ratio as well as differences in crop management (Yousefi et al., 2015). Furthermore, previous studies were conducted on smaller spatial extent and smaller sample size (Soltani et al., 2013). While irrigation always leads to higher yields (and GHG emissions) the differences are much smaller in the present study compared to previous studies. This also impacts the derived conclusions regarding the suitability and necessity for supplemental irrigation, which is of less importance in Golestan compared to other regions. However, it can be seen that irrigated production features a smaller standard deviation (SD) of yield indicating a yield stabilizing effect of irrigation (Shrestha et al., 2013).

With regard to GHG emissions irrigated production in average causes more than 3300 kg CO_2-eq ha^{-1}. This is more than twice as high as the 1600 kg CO_2-eq ha^{-1} emitted in average in rainfed production. However, both production systems entail high variation indicated by the large SD and difference between minimum and maximum values. Again the difference between irrigated and rainfed is rather small compared to the results of Yousefi et al. (2015), who identified GHG emissions of nearly 12,000 kg CO_2-eq ha^{-1} for irrigated wheat and only 725 kg CO_2-eq ha^{-1} for rainfed wheat in western Iran. Apart from differences in natural conditions, i.e. higher rainfall and lower irrigation requirements in Golestan compared to other parts of Iran, also differences in the data base, selected EFs and the definition of system boundaries may influence the GHG emission results. This is demonstrated by the very low value of only 280 kg CO_2-eq ha^{-1}, presented by Khoshroo (2014) for rainfed wheat production in Kohgilouye Province in southwestern Iran.

Finally, irrigated production entails a 62% higher (and hence significantly worse) PCF compared to rainfed production. While under rainfed production only 0.55 kg CO_2-eq are produced per kg of wheat grain, 0.89 kg CO_2-eq are produced per kg wheat grain under irrigated production. The higher yield in the irrigated production system does not compensate for its much higher GHG emissions leading to a significantly worse PCF. This complies with the findings of Ghorbani et al. (2011), who determined lower energy use and higher energy efficiency in rainfed compared to irrigated wheat production systems.

Calculating the PCF from the yield and GHG emissions data presented by Yousefi et al. (2015), irrigated production western Iran features a PCF of more than 1.5 kg CO_2-eq kg^{-1}, while rainfed production features a PCF of 0.37 kg CO_2-eq kg^{-1}. This again shows a much stronger difference compared to the present study's results. Comparing the results to studies from other wheat production regions in the world, the PCFs of Golestan's wheat farmers are rather high. For rainfed wheat production in Canada PCFs of 0.03–0.38 kg CO_2-eq kg^{-1} (Gan et al., 2014), 0.34 kg CO_2-eq kg^{-1} (Gan et al., 2012), and 0.42 kg CO_2-eq kg^{-1} (Gan et al., 2011) are reported. Brock et al. (2012) report even lower PCF in eastern Australia of 0.15 kg CO_2-eq kg^{-1} of rainfed wheat. For irrigated wheat production in Eastern China PCFs of 0.67 kg CO_2-eq kg^{-1} (Ha et al., 2015a), 0.85 kg CO_2-eq kg^{-1} (Yang et al., 2014) and 0.66 kg CO_2-eq kg^{-1} (Yan et al., 2015) are reported, while for New Zealand a PCF of 0.34 kg CO_2-eq kg^{-1} is reported (Barber et al., 2011). The differences in PCF of wheat production may be due to differences in natural production conditions, but also to crop management and resource use efficiency related factors (Mohammadi et al., 2013). Improving Golestan's farmers' crop management, especially related to timing, frequency and amounts of cropping measures, entails a large potential to improve productivity and environmental sustainability at the same time.

3.2. Impact of yield level on farmers' GHG emissions and carbon footprint

With farmers grouped according to their yield levels into high, medium and low yield groups, naturally their average yields differ significantly (*cf.* Table 4). The irrigated high yield group features the highest yields, the rainfed high yield group the second highest, the irrigated medium yield the third highest and so on. In contrast, the GHG emissions in the irrigated system are in all groups significantly higher than the GHG emissions in the rainfed system. This is mainly due to the generally lower input intensity in rainfed production and higher input intensity in irrigated production as also reported by Albrizio et al. (2010) and Mon et al. (2016).In both production systems the high yield group features the highest GHG emissions, followed by the medium yield group, while the low yield group produces least GHG emissions. This positive correlation of yield and GHG emissions highlights the trade-off between productivity and sustainability (see Table 5).

Same as the GHG emissions also the PCFs in irrigated production are in all groups significantly higher compared to rainfed production. Even the irrigated high yield group features a significantly worse PCF compared to the rainfed low yield group.

Comparing the three yield groups within each system the PCF of the high yield farmers is lowest (i.e., best), followed by the medium yield farmers, while the low yield farmers have the highest (i.e., worst) PCF. Hence, in both systems the higher yield levels in the high yield group overcompensate for the higher GHG emissions, leading to the lowest PCF in the high yield and the highest PCF in the low yield group. This indicates the potential for increasing yields and improving PCF by increased input intensities.

The contribution shares of the different GHG sources are illustrated for the six groups of farmers in Fig. 4. The area of each circle demonstrates the absolute amounts of GHG emissions per ha, which highlights the huge difference in GHG emissions between

Table 4
Average values of yield, GHG emissions, and PCF of the surveyed wheat farms in Golestan, grouped according to their yield level (high, medium, low) for irrigated and rainfed production; standard deviation, minimum and maximum values are given in parentheses. Different letters (a-f) behind the average values indicate significant differences between groups at 5% level as determined by Mann-Whitney test.

Groups of farmers		Yield (kg ha^{-1})	GHG (kg CO_2-eq ha^{-1})	PCF (kg CO_2-eq kg^{-1})	Number of farmers (N)
Irrigated	High yield	4828.5a (453.5; 4250–6500)	3884.5a (1445.5; 1392.8–8454.2)	0.80a (0.3; 0.3–1.9)	86
	Medium yield	3918.6c (146.3; 3700–4200)	3557.0a (1380.9; 1595.4–8608.3)	0.91a (0.3; 0.4–2.2)	78
	Low yield	2903.7e (494.6; 1200–3500)	2729.1b (1315.4; 1024.2–8730.6)	0.95a (0.4; 0.3–2.7)	95
Rainfed	High yield	4348.1b (551.9; 3750–6250)	1931.9c (662.1; 1073.5–5164.9)	0.45d (0.2; 0.2–1.3)	80
	Medium yield	3285.6d (285.0; 2900–3700)	1659.4d (508.8; 831.7–3975.1)	0.51c (0.1; 0.3–1.1)	108
	Low yield	1945.2f (598.4; 500–2700)	1246.0e (470.0; 373.5–3045.9)	0.69b (0.4; 0.3–3.5)	93

Table 5
Values of input flow data, including applied amounts, respective emission factors and respective GHG emissions of the example farm (references of specific emission factors are presented in Table 2).

Input	Input unit	Input amount	Emission factor (kg CO2eq kg-1)	GHG[b] (kg CO_2-eq ha^{-1})	Nitrogen (kg ha^{-1})
Seed	kg ha^{-1}	190	0.19	36.1	
Energy for irrigation	MJ ha^{-1}	4522.11	0.314	1419.94	
Mineral Fertilizer				569.08	144.65
Diammonium phosphate (N = 18%)	kg ha^{-1}	100	3.24	58.32	18
Potassium chloride (K_2O = 60%)	kg ha^{-1}	100	0.56	33.6	
Triple Superphosphate (P_2O_5 = 48%)	kg ha^{-1}	100	0.36	17.28	
Urea (N = 46%)	kg ha^{-1}	275	3.63	459.19	126.5
NPK compound (N:P_2O_5:K_2O = 15:8:15)	liter ha^{-1}	1	4.59	0.69	0.15
Organic fertilizer				**306.6**	**37.87**
Fresh ruminant manure	kg ha^{-1}	6000	0.044	264	30
Poultry manure	kg ha^{-1}	175	0.24[c]	42.6	7.87
Agricultural chemicals				**3.705**	
Herbicides	kg a.i.[a] ha^{-1}	0.018	23.1	0.416	
Fungicides	kg a.i. ha^{-1}	0.23	14.3	3.289	
Insecticides	kg a.i. ha^{-1}	0	18.7	0	
Diesel for machinery		**119.95**		**419.82**	
Soil tillage	liter ha^{-1}	39.99	3.5	139.97	
Sowing	liter ha^{-1}	17	3.5	59.5	
Fertilization	liter ha^{-1}	7.10	3.5	24.85	
Crop protection	liter ha^{-1}	6.6	3.5	23.1	
Harvest	liter ha^{-1}	32.37	3.5	113.29	
Transportation	liter ha^{-1}	16.89	3.5	59.11	
Crop residues					**56.57**
Root	kg ha^{-1}	1299	2.87%N[d]		37.28
Straw	kg ha^{-1}	862	2.47%N[d]		21.29

[a] .i. = active ingredient.
[b] GHG (kg CO_2-eq ha^{-1}) = Input amount (kg ha^{-1}) * Emission factor (kg CO_2-eq kg^{-1}).
[c] Derivation of EF for poultry manure explained in Table 6.
[d] Based on (MSU, 2016).

Table 6
Data used for deriving emission factor (EF) for poultry manure.

	Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)	Reference
Nutrient content (%)	4.5	2.7	1.4	(Ecochem, 2016)
Emission factor (kg CO_2-eq kg^{-1})	4.8	0.73	0.55	(Lal, 2004)

irrigated and rainfed production. As such, the “irrigated high yield” group features more than three times higher emissions compared to the “rainfed low yield” group.

In the irrigated production systems the energy use for irrigation is the strongest contributor accounting for about one third of total GHG emissions, with the highest share for the medium yield group and the lowest share for the low yield group. N_2O emissions from managed soil are the largest and second largest source of GHG emissions in the rainfed and irrigated production systems, respectively. In average they account for nearly 30% in irrigated production (927 kg CO_2-eq ha^{-1}) and around 45% in rainfed production (734 kg CO_2-eq ha^{-1}). The emissions stemming from manufacture and transportation of fertilizer are another relevant source of GHG emissions accounting to about 15% in irrigated and 20% in rainfed production.

With regard to diesel for machinery and seed it can be seen that in both production systems, the contribution share is increasing from the high yield, over the medium yield to the low yield group. These two inputs are applied at constant rates, as farmers cannot decrease (or increase) the intensity of these inputs. All farmers have to use a similar amount of seeds (sowing density) and have to conduct the same basic machine working steps (including tillage, sowing, harvesting). However, the high yielding groups (i.e. more productive) in both production systems obviously cultivate their crops more input intensive, especially with regard to fertilizer input, compared to the low yield groups. The contribution of chemical plant protection is very low and shows no big difference in the shares and absolute amounts between the production systems and three yield groups ranging from only 0.2%–0.5%.

Comparing irrigated and rainfed production systems it can furthermore be seen that energy for irrigation accounts for 30%–37% of total GHG emissions. However, the total GHG emissions per ha are more than double for irrigated compared to rainfed

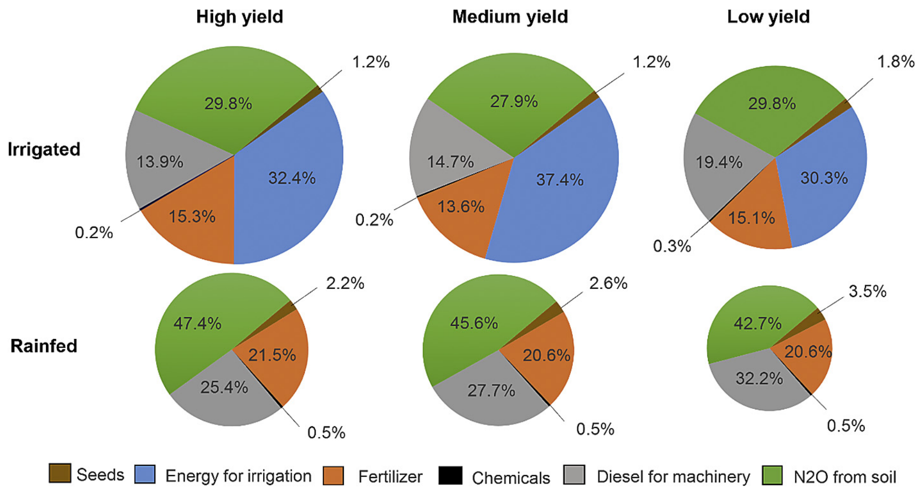

Fig. 4. Contribution of the different sources of GHG emission to total GHG emission per ha for irrigated and rainfed wheat production systems in Golestan Province subdivided into three groups of high, medium and low yield farmers; the area of the circles expresses the absolute amounts of GHG emissions per ha for each group.

production (*cf*. Table 3). This shows that the irrigated production is also more intensive regarding other inputs, especially fertilizer.

Compared to previous studies the contribution share of energy for irrigation to total GHG emissions is comparatively low in the present study. Yousefi et al. (2015) reported for wheat in western Iran that the highest contribution to GHG emissions in irrigated production was related to electricity (84%), while in rainfed production the highest contribution stemmed from N fertilizer use (65%). Similarly Khoshnevisan et al. (2013) identified electricity and chemical fertilizers to account for 74% and 14% of total GHG emissions of wheat production in Iran, respectively. There is evidence that the difference with previous studies is mainly due to differences in energy requirement for irrigation; about one-third of irrigated farmers in Golestan use surface water, which generally requires much fewer energy for pumping compared to groundwater use, which is increasingly exploited in the rest of Iran (Karimi

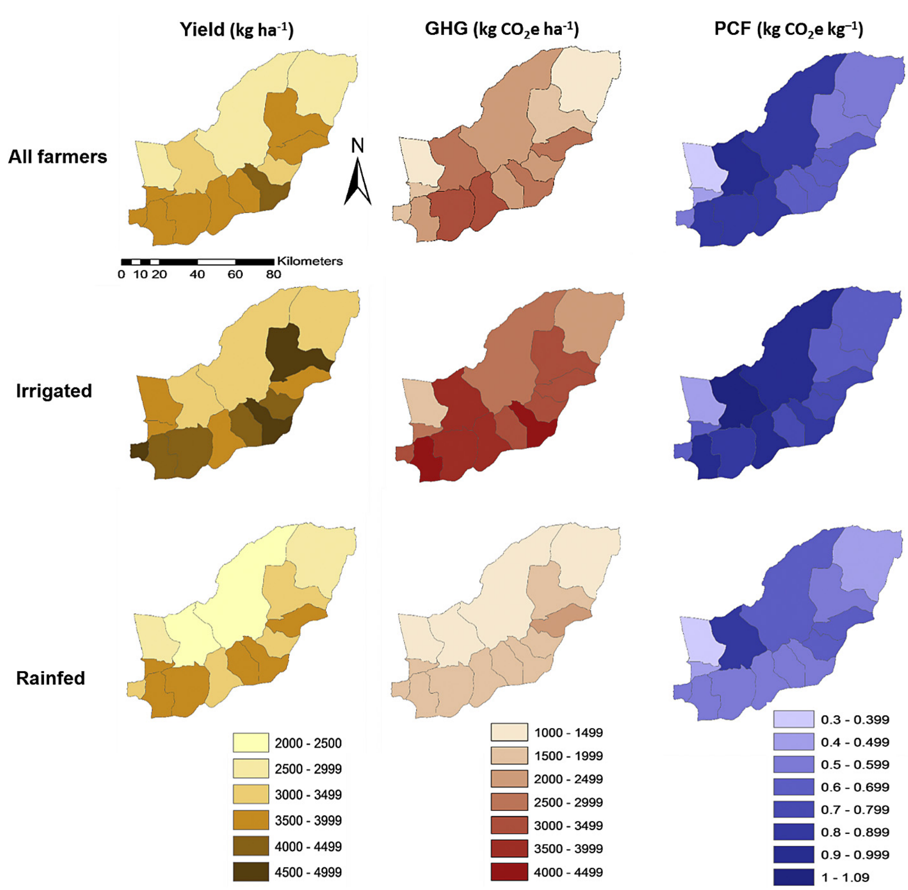

Fig. 5. Regional assessment of average wheat yields, GHG emissions, and PCF for all farmers, as well as for the irrigated and rainfed production systems in Golestan Province.

et al., 2012). Additionally, crop water supply through natural precipitation is generally higher in Golestan compared to most other regions of Iran. This consequently leads to reduced irrigation water demand and related energy requirements compared to other production regions.

Strong regional differences are revealed for farmers' average yield, GHG emissions and PCF between the counties located along the southeastern side and the counties along the northwestern side of Golestan Province (*cf.* Fig. 5). As such the northwestern counties feature much lower yield levels compared to the southeastern counties, which can be observed for all farmers as well as for irrigated and rainfed production. Average yield levels span from less than 2500 kg ha^{-1} under rainfed conditions in counties of the northwest to more than 4500 kg ha^{-1} under irrigated conditions in counties of the southeast. The spatial yield variations can partly be explained by the climatic gradient from mountainous (southeast), mediterranean (northwest) and semi-arid (northeast) climate. However, even under irrigated conditions, where drought stress is eliminated, the spatial gradient between the southeast and northwest remains. Therefore, additional factors must be responsible for the spatial differences in productivity, which are beyond the scope of the present study.

Looking at the spatial variation of average GHG emissions per ha a high parallelism of GHG emissions and yield levels is revealed. The analysis shows that the southeastern counties feature much higher emission values compared to the northwestern counties. While under rainfed conditions the southeast-northwest gradient is strongly pronounced, under irrigation some northwestern counties feature similar GHG emissions like the southeastern counties. The emissions range from below 1500 kg CO_2-eq ha^{-1} under rainfed production in all northwestern counties to more than 4000 kg CO_2-eq ha^{-1} under irrigated production in some southeastern counties. The GHG emissions per ha provide a strong indication on the level of production intensity (Yan et al., 2015). Hence, the spatial correlation of yield and GHG emissions confirms the above described trade-off between productivity and environmental sustainability also for the sub-regional level.

For average PCF no such distinct spatial pattern appears compared to yield and GHG emissions. Looking at all farmers' values it can be seen that the central counties feature the highest values and the most northwestern and northeastern counties feature the lowest values. The values range from below 0.4 kg CO_2-eq kg^{-1} under rainfed production in the northwest to more than 1 kg CO_2-eq kg^{-1} under irrigated production in some central counties. Irrigated production generally features much higher values compared to rainfed production. The spatial heterogeneity highlights that a diverse combination of factors determines the local PCFs, including climatic conditions, input intensity and other factors (e.g., extension quality, irrigation infrastructure, local soil conditions), which could not be captured by the present analysis.

4. Conclusions

This study investigated productivity and environmental impact of wheat production in Iran using GHG emissions and PCF as environmental sustainability indicators. The huge heterogeneity identified among the 540 surveyed wheat producers with regard to yield, GHG emissions and PCF, highlights the potential for improving crop management of a large share of farmers. In comparison irrigated production realizes significantly higher yields than rainfed production. However, the 22% or 704 kg ha^{-1} higher yields in irrigated production are realized at the cost of 110% or 1767 kg CO_2-eq higher GHG emissions ha^{-1} in irrigated compared to rainfed production. This ultimately results in a significantly worse PCF of irrigated (0.89 kg CO_2-eq kg^{-1}) compared to rainfed wheat (0.55 kg CO_2-eq kg^{-1}). The strong differences in GHG emissions between irrigated and rainfed production are largely caused by the energy required for irrigation, but also by higher fertilizer input intensity in irrigated compared to rainfed production. Accordingly, the major contributors to total GHG emissions of wheat production are energy for irrigation (only in irrigated production), N_2O emissions related to fertilization and residue handling, diesel for machinery, and emissions related to fertilizer production and transport. The comparatively high GHG emissions and PCF for both irrigated and rainfed production compared to results from other production regions indicates the potential for improvement of crop management regarding increased output and more efficient use of inputs.

Clustering farmers into three groups revealed that among irrigated and rainfed producers higher yields are related to higher GHG emissions but to lower PCF. It furthermore showed that the group of the lowest yielding rainfed farmers realized a significantly lower, i.e. better PCF compared to the highest yielding irrigated group. However, this also indicates that aiming for higher yields through increased input intensities may lead to improved, i.e., lower PCF. Hence, input intensity should be adjusted in irrigated and rainfed production, to better balance productivity and climate impact in wheat production. The results indicate that it may be most viable for water-scarce regions to aim for an input-efficient middle-yield agricultural practice. While an extensive low-yield practice might lead to food security concern, an input-intensive high-yield practice might cause serious environmental and ecological problems impeding a sustainable agricultural development.

The regional analysis showed strong variations within Golestan; however the trade-offs between productivity and environmental sustainability were confirmed on the sub-regional level. The trade-off between productivity and environmental sustainability identified in irrigated vs. rainfed wheat production in Golestan urges the question of the viability of supplemental irrigation. Competition for scarce water resources continuously increase in Iran (Mehrparvar et al., 2016) and many other water scarce agricultural production regions of the world (Mancosu et al., 2015). Hence, it is questionable whether the 22% yield increase at the cost of tremendously increased (110%) GHG emission (as determined in the present study) justifies the application of supplemental irrigation for wheat production. However, additional research is required that investigates the site specific crop water situation in more detail, which was beyond the scope of the present study.

Acknowledgments

The University of Zabol and Julius Kühn-Institut provided facilities for this research, which is greatly acknowledged. The authors furthermore appreciate the support of Dr. Habib Kashiri, the staff of the Agriculture Organization of Golestan Province during the data collection, and Dr. Ling Yee Khor from University of Hohenheim for statistical support.

Appendix

Calculation of GHG emissions and PCF of wheat production of a specific example farm.

$$\text{Total GHG } (\text{kg } CO_2 - \text{eq ha}^{-1}) = \text{GHG(Seed + Irrigation + Mineral fertilizer + Organic fertilizer+}$$
$$\text{Agricultural chemicals + Diesel for machinery) + } N_2O \text{ from managed soil}$$
$$= (36.1 + 1419.94 + 569.08 + 306.6 + 3.705 + 419.82) + 1475.7$$
$$= 2755.25 + 1475.7$$
$$= 4230.95$$
$$\text{Yield } (\text{kg ha}^{-1}) = 5300$$
$$\text{PCF } (\text{kg } CO_2 - \text{eq kg}^{-1}) = \text{Total GHG / grain yield}$$
$$= 4230.95/5300$$
$$= 0.798$$

Calculation of straw and root biomass in crop residues following Lal (2004).

$$\begin{aligned} &\text{Yield}(\text{kg ha}^{-1}) &&= 5300 \\ &\text{Grain : Straw} - \text{Ratio} &&= 1.23 \\ &\text{Shoot : Root} - \text{Ratio} &&= 7.4 \end{aligned}$$

$$\text{Straw biomass } (\text{kg ha}^{-1}) = \text{Yield/Grain : Straw} - \text{Ratio}$$
$$= 5300/1.23$$
$$= 4308.9$$
$$\text{Root biomass}(\text{kg ha}^{-1}) = (\text{Yield + Straw biomass})/\text{Shoot : Root} - \text{Ratio}$$
$$= (5300 + 4308.9)/7.4$$
$$= 1299$$

While all root biomass remains as residue in the field, most local farmers (including the presented example farm) sell the wheat straw and only the stubble remain in the field. Hence, for those farms it was decided to consider only 20% of the total straw biomass as straw residue.

$$\begin{aligned} \text{Straw residue}(\text{kg ha}^{-1}) &= (\text{Straw biomass * 20\%}) \\ &= (4308.9*20\%) \\ &= 862 \text{ kg} \end{aligned}$$

Calculation of N_2O emissions from managed soil following IPCC (2006).

$$N_2O_{direct} = (F_{SN} + F_{ON} + F_{CR})*EF_1*\gamma_{N2O}$$
$$= (144.65 + 37.88 + 56.6)*0.01*44/28$$
$$= 3.76$$
$$N_2O_{(ATD)} = (F_{SN}*EF_4*Fras_{GASF} + F_{ON}*EF_4*Fras_{GASM})*\gamma_{N2O}$$
$$= (144.65*0.01*0.1 + 37.88*0.01*0.2)*44/28$$
$$= 0.346$$
$$N_2O_{(L)} = (F_{SN} + F_{ON} + F_{CR})*EF_5*Fras_{LEACHING}*\gamma_{N2O}$$
$$= (144.65 + 37.88 + 56.8)*0.0075*0.3*44/28$$
$$= 0.846$$
$$N_2O_{indirect} = N_2O_{(ATD)} + N_2O_{(L)}$$
$$= 0.346 + 0.85$$
$$= 1.192$$
$$N_2O_{total} = N_2O_{direct} + N_2O_{indirect}$$
$$= 3.76 + 1.192$$
$$= 4.952$$
$$GHG_{N2O*} = N_2O_{total}*GWP_{N2O}$$
$$= 4.952*298$$
$$= 1475.7$$

where F_{SN}, F_{ON}, and F_{CR} represent the N amount of mineral fertilizers, organic materials and crop residues applied to soil (Dubey and Lal, 2009). $N_2O_{(ATD)}$, and $N_2O_{(L)}$ are N_2O emissions from atmospheric deposition, and leaching and runoff of nitrogen additions from managed soils, respectively. EF_1, EF_4, and EF_5 are the EF_s (emission factors) of N_2O emissions from inputs, atmospheric deposition, leaching and runoff of N on soils. $Fras_{GASF}$, $Fras_{GASM}$, and $Fras_{LEACHING}$ are the fraction factors of atmospheric deposition of N volatilized from mineral fertilizer, organic materials, and leaching from managed soil; γ_{N2O} is the mass conversion factor (44/28 g g^{-1} mol mol^{-1}) (IPCC, 2006).

Derivation of emission factor for poultry manure.

As no emission factor (EF) for dry poultry manure was available in literature, an EF was derived by substitution method. It was assumed that the application of Nitrogen, Phosphorus and Potassium from manure can substitute the application of Nitrogen, Phosphorus and Potassium from mineral fertilizer. Hence the contents of pure Nitrogen, Phosphorus and Potassium in poultry manure (Ecochem, 2016) were multiplied by the EFs of pure Nitrogen, Phosphorus and Potassium from mineral fertilizer (Lal, 2004).

$$EF_{poultry\ manure} = (\%N*EF_N) + (\%P_2O_5*EF_{P2O5}) + (\%K_2O*EF_{K2O})$$
$$= (4.5\%*4.8 \text{ kg } CO_2 - \text{eq kg}^{-1}) + (2.7\%*0.73 \text{ kg } CO_2 - \text{eq kg}^{-1})$$
$$+ (1.4\%*0.55 \text{ kg } CO_2 - \text{eq kg}^{-1})$$
$$= 0.24 \text{ kg } CO_2 - \text{eq kg}^{-1}$$

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